BEHAVIOR OF BIAXIALLY PRESTRESSED CERAMIC PLATES UNDER THERMAL LOADING

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ABSTRACT

The use of biaxial prestressing as a means of reducing or preventing damage to ceramic specimens under thermal stress was studied. The extent of structural damage of the ceramic material, after thermal stressing, was evaluated by determining the degradation in its bending strength. The experimental results indicated that the residual bending strength of the thermally stressed plates increased linearly with increasing levels of precompression, until a level of prestress was reached which was equal to the bending strength of the virgin material. Prestress levels of this value, or greater, for the conditions of this experimentation, appeared to provide full protection against damage under the imposed thermal load.

[redacted]

I. INTRODUCTION

Extensive consideration has been given to the susceptibility of ceramic materials to cracking under thermal stress, beginning as early as 1838 by Duhamel,[1] and followed by numerous investigations, including an early quantitative treatment by Winkelmann and Schott[2] (1894). No attempt is made here to review the many significant literature contributions in this field of study, although a few selected items of particular value are given in References 3-6. The recent work of Huang[7] is of specific interest, wherein the deterioration of strength of a brittle porous material, after loading in tension, is predicted. Huang calculated the residual strength of porous ceramic beams after a heating and cooling cycle, using a formulated degradation factor, assuming that tensile stresses tend to enlarge flaws. Huang carried on limited experimentation with porous ceramic beams, and found that the degradation of strength, following thermal stressing, could be predicted satisfactorily with his formulated factor.[7]

If, following the above reasoning, one considers structural damage of a ceramic to be due to tensile stresses, it may be expected that ceramic structures designed to minimize tensile stresses will have increased resistance to failure under thermal cycling. Therefore, the use of prestressing is a possible means of increasing the resistance of ceramics to damage under thermal stress. A preliminary study[8] of the deterioration of strength of some uniaxially-prestressed ceramic specimens, after thermal cycling, indicated that some significant reduction in damage was provided by the prestressing used.

The purpose of the research described herein was to evaluate the effect of biaxial prestressing on the resistance to damage of porous ceramic plates under thermal loading.

II. EXPERIMENTAL

In this experimentation, a ceramic plate was biaxially-precompressed in the plane of the plate; then a specific area of one face was heated, under reproducible conditions, and the plate was allowed to cool. Figure 1 shows

 [redacted]

the loading conditions. Following the thermal cycle, the specimen was unloaded, and its bending strength determined. Some details of the equipment and procedure follow:

(1) Ceramic Plates

The ceramic members tested were plates nominally 1/2" x 6" x 6" in size. The plates were manufactured with a high-talc (western type) wall-tile body, using factory production equipment for press-forming and firing. X-ray analysis indicated that the chief crystalline phases present in the fired plates were enstatite, quartz, diopside and feldspar. Some representative property values for these plates were:

Apparent porosity.	= 29.5 ± 1% (By A.S.T.M., C 20-46)
Water absorption	= 14.9 ± 1% (By A.S.T.M., C 20-46)
Bulk density	= 1.81 gm/cm^3 (By A.S.T.M., C 20-46)
True specific gravity	= 2.735 (By A.S.T.M., C 20-46)
Modulus of rupture	= 3100 ± 500 psi

(2) Prestressing Fixture

A fixture for biaxial prestressing, which has been described by Ali et al,[9] was used. This fixture is composed of steel I-beams fastened to form a square frame. Prestressing loads may be applied in the x and y directions by two calibrated hydraulic jacks, each of 30 tons capacity. The prestressing loads were transmitted from the jacks through spherical bearings onto grooved bearing blocks, and thence onto the test plate. Thin, rubberized asbestos gasketing was used to cover all load-bearing surfaces of the ceramic plate to help distribute loads.

(3) Thermal Source

The thermal source was composed of five infrared quartz lamps, each rated at 700 watts, arranged in an array in a ceramic reflector.* The lamps and the reflector were fixed to a transite block through which air may be passed for cooling the lamps. The thermal source was mounted in a housing which could be positioned above the prestressing fixture.

The prestressing fixture and thermal source are shown in Figure 2, and some details of apparatus arrangement are indicated in Figure 3.

(4) Experimental Procedure

In preparation for a thermal stressing run, a stainless steel shield with a three-inch diameter aperture was placed over the ceramic plate, and the positions of the lamps and the steel shield were so adjusted that the center of the ceramic plate and the aperture center coincided. The thermal source then was turned on for a period of 15 minutes, following which the plate was allowed to cool to room temperature. (These conditions were selected because non-prestressed test plates always cracked during this cycle.) Typical time-temperature relationships at different locations of the plate are shown in Figure 4. After the heating and cooling cycle was completed, the plate was unloaded, carefully taken out of the fixture, and tested, using an Instron testing machine to determine its strength in bending. A number of specimens was tested at each prestressing level, up to a maximum prestressing level of 4683 psi.

IV. RESULTS

Figure 5 shows the distribution of bending strength of the plates as received (plates which were subjected to neither thermal stresses nor prestressing). Table I gives the results for the bending strength tests on the plates which were subjected to thermal stresses while biaxially prestressed. Figure 6 shows a plot of these data. A straight line was drawn through the averages of the experimental points by the method of least squares. During thermal stressing of plates which were prestressed below a level of 2233 psi, noises were heard at different times which may have been produced by cracking of these plates.

*Manufactured by Pyrometric, Inc., Seattle, Washington.

V. DISCUSSION

Since the maximum induced thermal stresses were sufficient to fracture all unprestressed specimens, the strength of the specimens is zero in the unprestressed condition after being subjected to thermal stresses. At this stage it will be convenient to introduce "the residual bending strength, σ_R," which is defined as the bending strength of the prestressed ceramic plates after being subjected to thermal stresses. Figure 6 indicates that there is a linear increase of the residual bending strength σ_R with biaxial prestress σ_A. At a prestressing level of 3067 psi, the residual bending strength σ_R is roughly equal to the bending strength σ_V of the virgin specimens (as received). At higher prestress levels, σ_R remains constant and approximately equal to σ_V. This prestressing level is significant only for the level of thermal stresses induced in this case, as it is the minimum amount of prestress that has to be applied to the plates in order that the residual bending strength will be equal to the bending strength of the virgin material.

The analysis of experimental results involves, first, an evaluation of thermal stresses; and second, the correlation of σ_R with σ_A.

(1) Evaluation of Thermal Stresses

The evaluation of thermal stresses requires an estimation of temperature distribution in the plate based upon the following assumptions:

a. Since the plate is heated by irradiation of a circular area (3" dia.) of one face, only that central portion of the plates will be considered for calculating temperature, as well as stress, distribution, as the most severe stresses will be produced in this portion.

b. That the temperature distribution at a specific time is uniform in the Z direction, that is, perpendicular to the 6" x 6" face, in the central heated portion of the plate.

c. That the central portion is infinite in the X and Y directions, or in plane of the 6" x 6" face.

d. That the properties of the materials are constant over the temperature range experienced.

With these assumptions, and the use of the Fourier equation for heat transfer in the Z direction, the temperature T at any point, in the central portion of the plate under consideration, and at a specific time, is given by:

$$T = \frac{T_f - T_b}{b^2} Z^2 + T_b \tag{1}$$

where T_f = temperature of the irradiated surface

T_b = temperature of the surface opposite to that irradiated

b = thickness of the plate (in the Z direction)

Z = distance from the face opposite to the irradiated surface

Since the experimental procedure involving heating and cooling periods produced a maximum temperature differential at a time of about ten minutes (see Figure 4), it was of interest to calculate the temperature distribution in the central heated portion of the plate, in the Z direction, using Equation (1), and having the measured surface temperature T_f, at the end of the ten minutes time (see Figure 7). From a knowledge of the temperature distribution, the thermal stresses in the central portion of the plate may be approximated with use of the following equation[10] (for an infinite slab):

$$\sigma_x = \sigma_y = \frac{Ea}{1-\mu} (Ta - T) \tag{2}$$

where E = Young's modulus of elasticity = $5.42 \times 10^{+6}$ psi (Measured, A.S.T.M., E 6-62 sec. 5)

a = coefficient of linear thermal expansion, measured = 4.54×10^{-6} in/in -^{o}C

μ = Poisson's ratio for the material = 0.25 (assumed)

T_a = temperature of the plate at the point of zero stress = 628^{o}F (calculated assuming the above temperature distribution)

The thermal stresses in the central portion of the plate, after a heating time of ten minutes, were calculated as indicated above (Reference 11 provides detailed sample computations), and are shown in Figure 7. It can be seen that a maximum compressive stress exists in the irradiated surface, at this time, and that the surface of the opposite face is subjected to a maximum tensile stress. Since ceramics are much weaker in tension than in compression, it may be assumed that failure of the ceramic will result when the tensile stress exceeds the tensile strength of the material, and, following the reasoning of Huang,[7] that lesser tensile stresses may damage the ceramic by enlarging flaws.

It was of interest to note that the calculated maximum tensile stress (from Equations 1 and 2) at ten minutes was 3060 psi, which agreed remarkably well with the measured value of the bending strength (3100 ± 500 psi) of the virgin material considering the approximations made. This result supported the usefulness of the calculated value of thermal stress, which is used later in interpreting the results.

(2) Correlation of the Residual Bending Strength σ_R With Applied Prestress σ_A

As mentioned previously, the residual bending strength σ_R is defined as the bending strength after thermal cycling. σ_R was determined experimentally in this study, and the results are given in Figure 6 and Table I. In addition, a rough prediction of σ_R may be made with the following equation:

$$\sigma_R = \sigma_V + \sigma_A - \sigma_T \tag{3}$$

where σ_V = bending strength of the virgin material

σ_A = the imposed biaxial prestress

σ_T = maximum stress (tensile) produced by the thermal cycle, as given by Equation (2).

Equation (3) assumes that a resultant of thermal stress and prestress may be obtained by superposition. Predicted values of σ_R using Equation (3) also are plotted in Figure 6, and are in reasonably good agreement with measured values.

These results may be explained by assuming that tensile (thermal) stresses enlarge already existing flaws, which causes weakening or complete failure of the ceramic. When a prestress is applied, it tends to reduce or prevent the enlargement of flaws, thus reducing, or preventing, damage.

(3) Summary and Conclusions

The effect of thermal stresses on the residual bending strength (σ_R) of the biaxially prestressed ceramic plates was studied in the prestressing range from 0 to 4463 psi. Biaxial prestressing provided various degrees of protection against damage by thermal cycling for conditions of this experiment, depending upon the level of prestress. The maximum induced thermal stress in tension was equivalent to the bending strength (σ_V) of the specimens as received. When there was no prestress, the residual bending strength of the specimens was zero. As the biaxial prestress (σ_A) was applied, there was a linear increase in the residual bending strength σ_R of the specimens with σ_A up to a significant prestressing level (which was equal to σ_V), where it remained constant thereafter. This significant prestressing level is the sufficient extent of biaxial prestress required to protect the plates from damage by thermal stresses. However, if the sum of the applied prestress and thermally induced compressive stress exceeds the compressive strength of the material compressive failure may be expected to occur.

The protection provided by prestressing against damage by thermal cycling may be explained by the reduction of tensile stresses, which in turn reduces the likelihood of enlargement of critical flaws. For the conditions of this experiment, it was possible to completely protect the ceramic plates against damage by a sufficient level of biaxial prestress.

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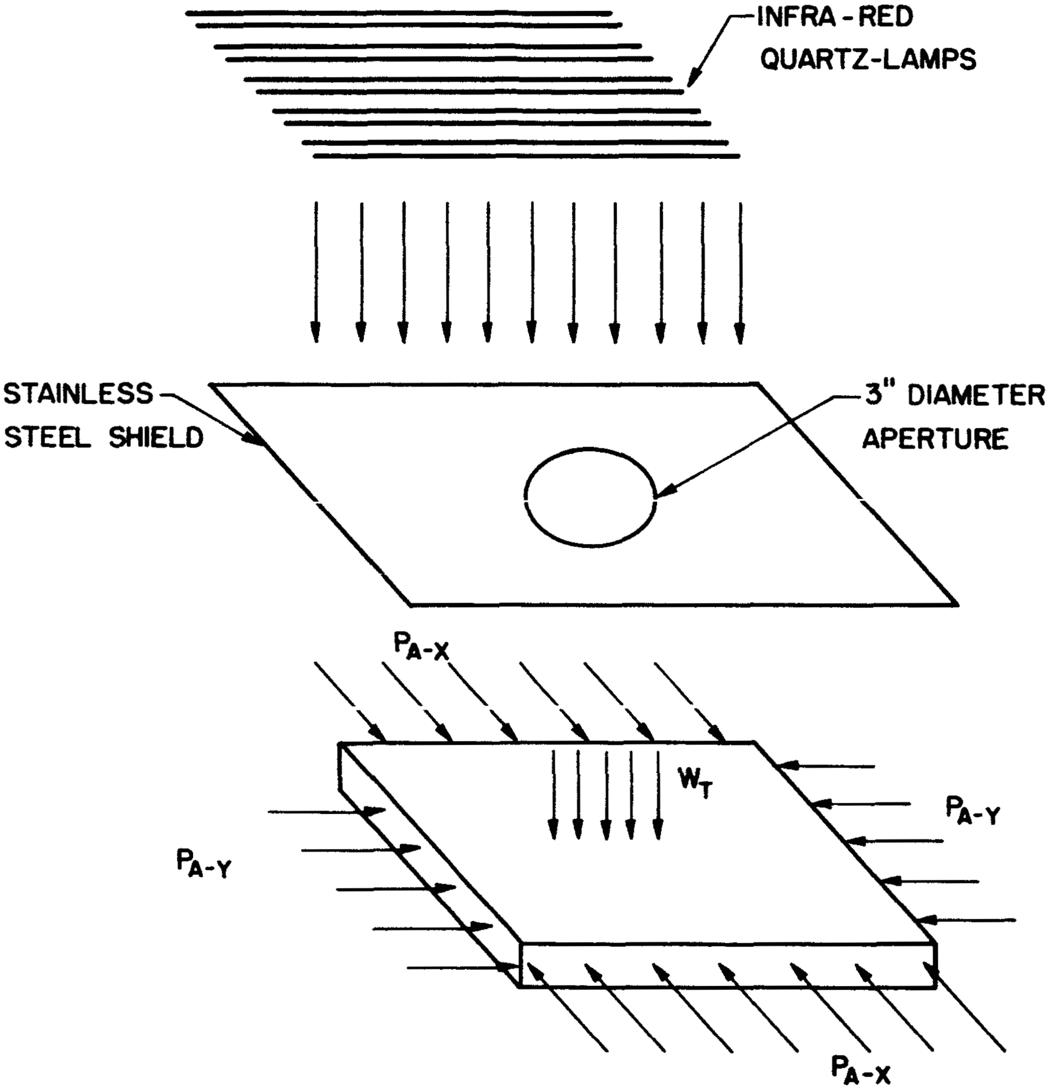
TABLE I

SUMMARY OF RESULTS

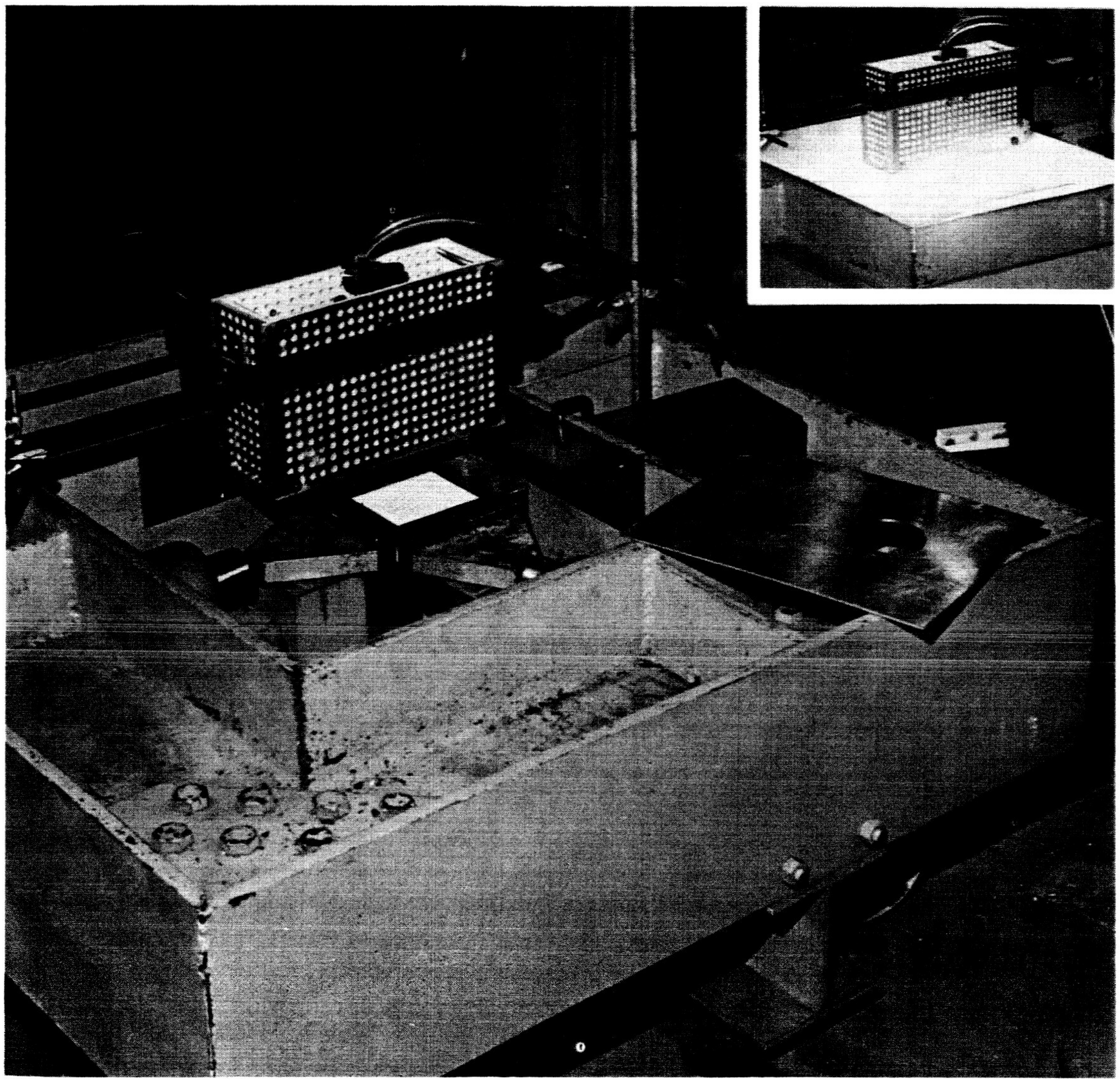
Prestressing Level in psi	Effective Modulus of Rupture in psi Min.	Mean	Max.	No. of Tests	Standard Deviation	% S.D/Mean
217	0	140.03	923	12	268	192
423	185	800	1365	10	424	46
633	185	1161	1845	9	503	43.4
1050	592	1372	2070	11	436	31.8
1467	1475	1788	2250	9	238	13.3
1880	1695	2059	2700	12	349	17
2230	1660	2358	2750	7	372	15.8
2650	1735	2520	3320	10	506	20.1
3067	2310	2788	3340	10	367	13.1
3467	2180	2787	3260	10	338	12.2
3867	2250	2789	3480	12	374	12.9
4300	2540	3012	3430	9	109	3.6
4683	2340	2965	3300	10	345	11.6



P_{A-X} = PRESTRESSING IN X-DIRECTION
P_{A-Y} = PRESTRESSING IN Y-DIRECTION
W_T = THERMAL LOAD (APPLIED OVER 3" CIRCULAR AREA)

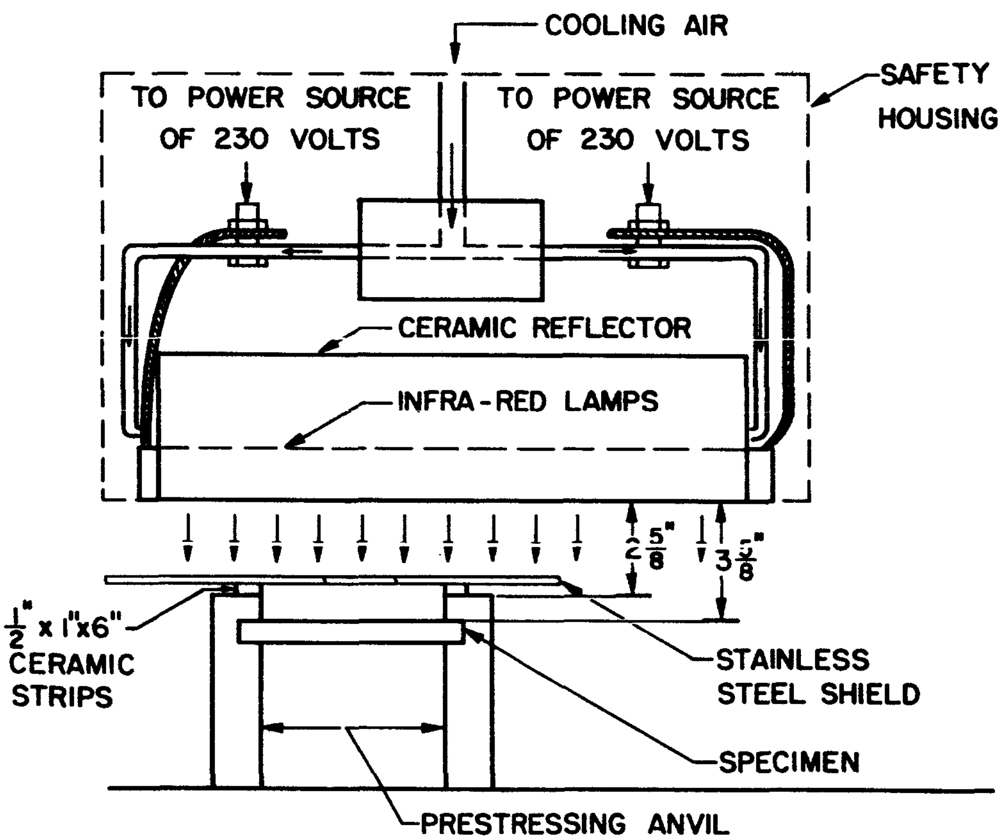
THERMAL LOADING OF A BIAXIALLY PRESTRESSED CERAMIC PLATE

FIGURE 1



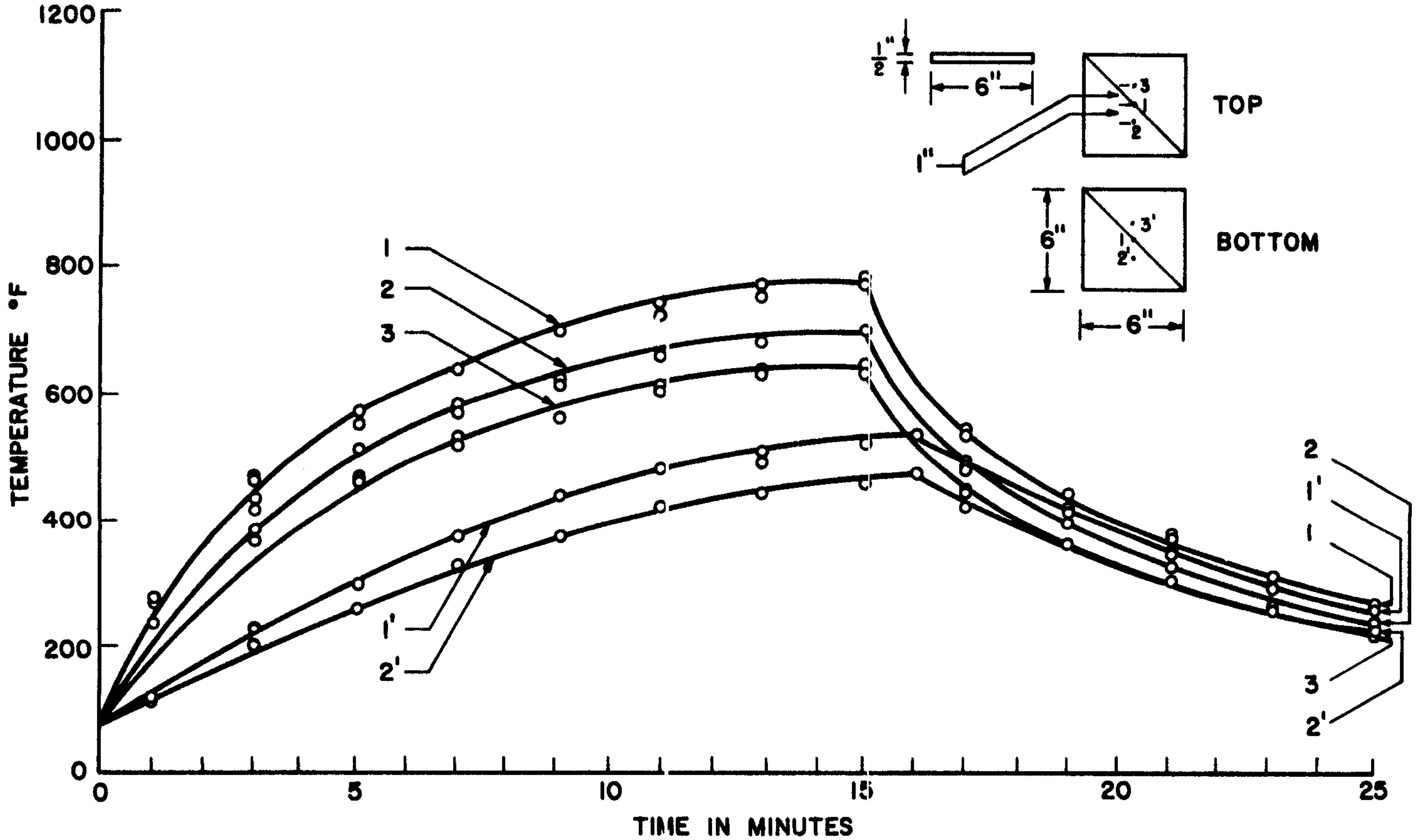
PRESTRESSING FIXTURE WITH HEATING LAMPS
PLACED OVER THE PLATE
INSERT: LAMPS IN OPERATION

FIGURE 2



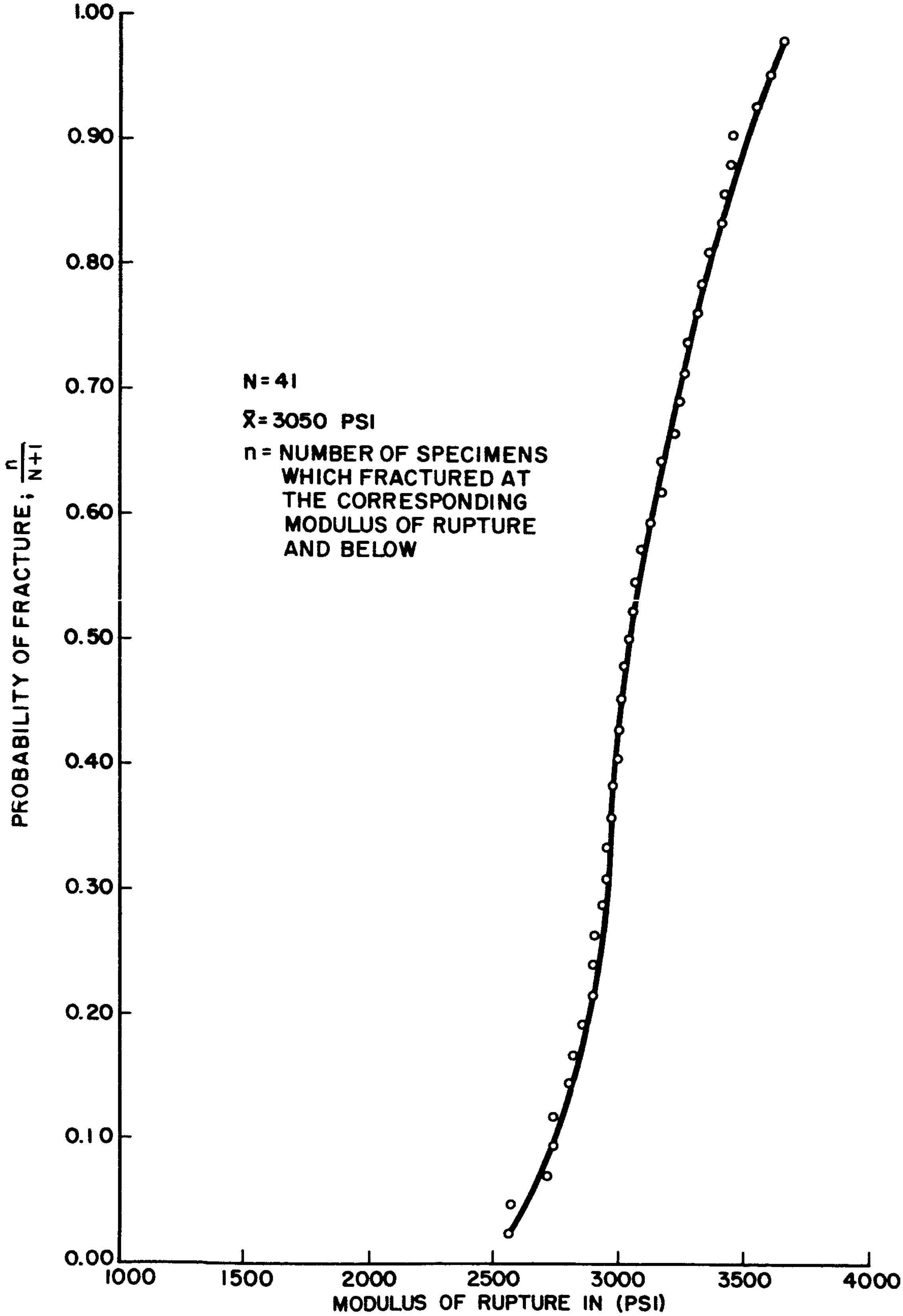
SCHEMATIC DIAGRAM SHOWING THE POSITION OF HEATING LAMPS AND SPECIMEN

FIGURE 3



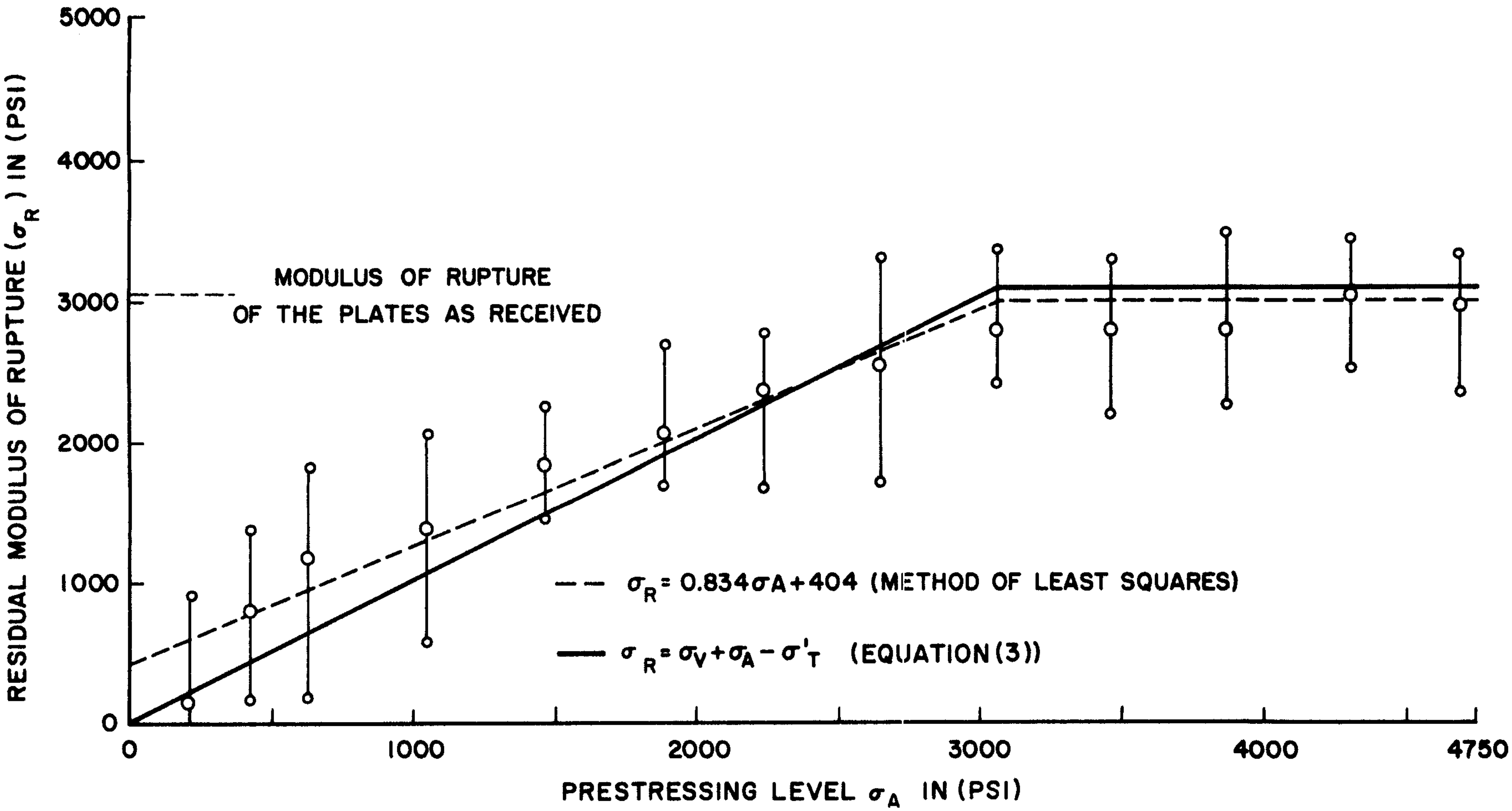
TIME-TEMPERATURE CURVES AT DIFFERENT POINTS ON THE PLATE

FIGURE 4



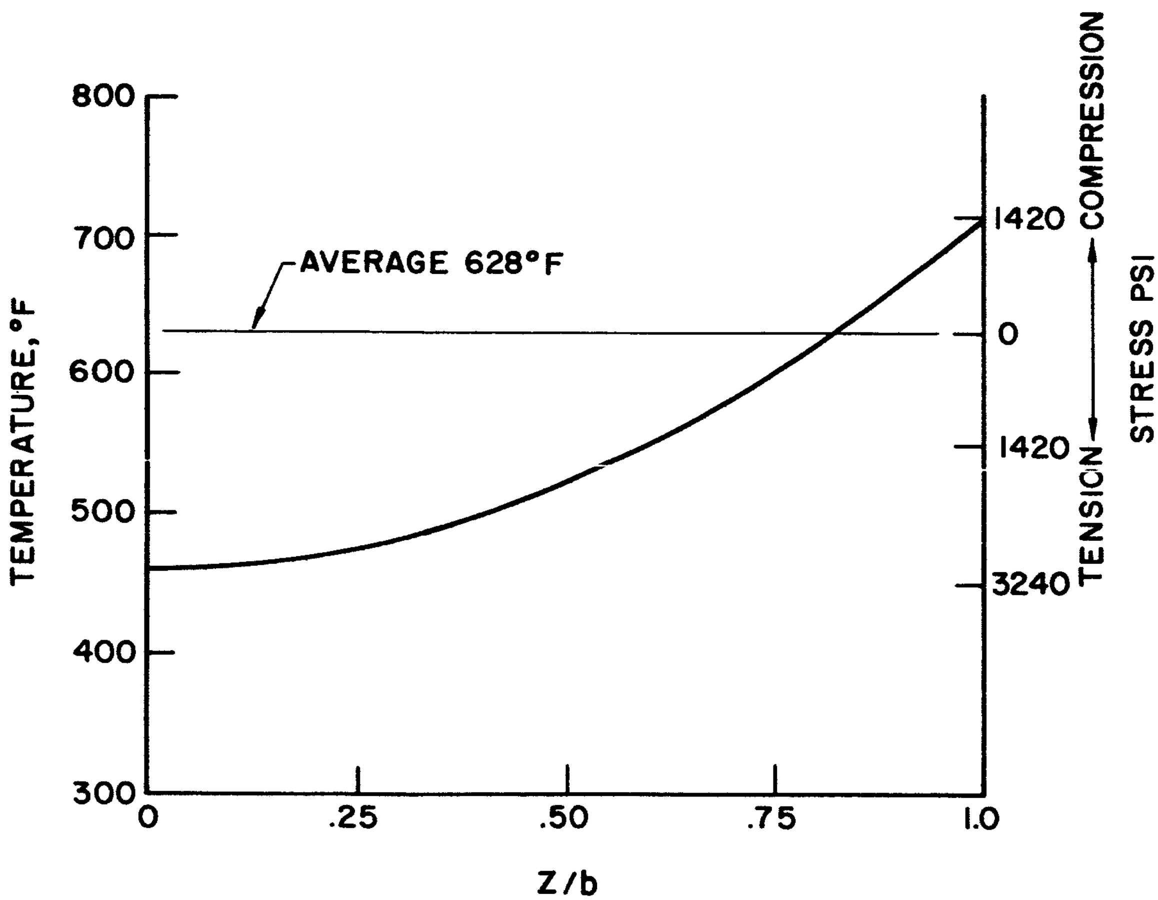
DISTRIBUTION OF MODULUS OF RUPTURE OF THE PLATES AS RECEIVED

FIGURE 5



VARIATION OF RESIDUAL BENDING STRENGTH (σ_R) WITH BIAXIAL PRESTRESS (σ_A)

FIGURE 6



THEORETICAL TEMPERATURE DISTRIBUTION AND CORRESPONDING STRESS DISTRIBUTION AFTER 10 MINUTES OF HEATING. b = CONSTANT PLATE THICKNESS, z = DISTANCE FROM THE COLD FACE

FIGURE 7